K/Ar ages from the Guerrero transect date four thermotectonic events affecting the North America Plate in Mexico from 301 Ma TO 29 Ma

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Abstract. Because of questions regarding the validity of proposed accreted terranes, the tectonostratigraphic evolution of the southern margin of the North America plate in Mexico remains controversial. Here we bring new data to this debate. We report whole rock K/Ar isotopic ages for 19 hypabyssal igneous and low grade metamorphic rock samples collected on a 300 km long, W-E geological transect in southern Mexico. Analysis of these new data, using structural and stratigraphic information from the transect and frequency plots of isotopic ages reported elsewhere in Mexico and the U.S. Cordillera, shows that four thermotectonic events affected the transect, most of Mexico and the U.S. Cordillera. These events are: I. (301 Ma ±8 Ma), metamorphism/uplift due to the Alleghenian Orogeny; II. (221 Ma ±5 Ma), metamorphism/uplift due to the Sonoman Orogeny; III. (94.4 ±2.4 — 82.8 ±2.2 Ma), metamorphism/uplift, thin-skinned tectonics and magmatism due to Sevier Orogeny; and IV. (50.9 ±1.3 Ma — 28.8 ±0.9 Ma), magmatism and normal faulting due to the waning Laramide Orogeny and onset of Basin and Range extension. The map pattern of regions affected by these four events is independent of proposed terrane boundaries in Mexico; and shows that most of the present real estate of Mexico has been a coherent part of the North America plate since at least Pennsylvanian time.

1. Introduction

The tectonostratigraphic evolution of the southern margin of the North America plate in Mexico remains controversial. Much of the debate focuses on the validity of proposed accretionary terranes of supposedly unknown paleogeographic affinity, which were postulated to have collided with North America during the Laramide Orogeny [*Campa and Coney*, 1983; *Centeno-Garcia et al.*, 1993a, 1993b; *Sedlock et al.*, 1993; *Talavera-Mendoza et al.*, 1993; 1995]. *Lang et al.* [1996] disputed four of these terrane boundaries in southern Mexico on the basis of mapping along a 30x250 km transect, mostly in Guerrero state. They argued that the region was part of the southern margin of the North America plate during the Cretaceous, consistent with the interpretations of *Campa* [1985], *Guzman* [1950] and *Jenny* [1933] that the region is the southern arm of the Mexican fold and thrust belt that is well-defined north of the Trans-Mexican Volcanic Belt [*De Cserna*, 1989].

Here we bring new data to this debate; we report K/Ar isotopic ages of 19 low grade metamorphic and hypabyssal igneous rocks from the Guerrero transect (Figure 1 and Table 1). These ages date at least four thermotectonic events that affected Mexico and the North American Cordillera during Pennsylvanian (301 Ma) through Late Oligocene (29 Ma) time. Results do not support the notion that southern Mexico is a collage of terranes accreted during "Laramide" (Campanian-Eocene) [*Campa and Coney*, 1983] or mid-Cretaceous [*Sedlock et al.*, 1993, figures 37 and 38] time. Instead, our results indicate that southern Mexico has been a coherent part of the North America plate since at least middle Pennsylvanian time.

2. Location, structure and stratigraphy

The Guerrero transect (Figure 1) [*Lang et al.*, 1996], centered approximately 120 km south of Mexico City, runs nearly W-E from southeastern Michoacan through northern Guerrero, southern Puebla and into Mexico State. For this study, we extended the transect 40 km to the east based on our mapping and previous work by *De Cserna et al.* [1980], *Erben* [1956], and *INEGI* [1985a].

The major structures exposed on the transect are: 1) NW to NE striking thrust faults and associated folds [*Cabral-Cano et al.*, 1999a; *Johnson et al.*, 1991 and 1992; *Lang and Frerichs*, 1998], and 2) NW, N, and EW striking high angle faults with normal offset [*Cabral-Cano et al.*, 1999a; *Jansma and Lang*, 1997]. The westward dip of most thrust faults and the asymmetry of folds record predominantly eastward vergence. Outcrop-scale kinematic data by *Cabral-Cano* [1995] and *Cabral-Cano et al.* [1999a] between sample site 6 and 12 (Figure 1) support this interpretation. The geometric similarity of these structures to those in the Sierra Madre Oriental fold and thrust belt of northern Mexico suggests that "Laramide" orogenesis extends into this part of southern Mexico [*Campa*, 1985; *Johnson et al.*, 1991; *Lang and Frerichs*, 1998; *Lang et al.*, 1996].

Cross section balancing across the entire Guerrero transect (Figure 1), yields E-W shortening due to folding and thrust faulting of approximately 60 km; and horizontal translation on individual thrust faults of as much as 13 km [*Lang et al.*, 1996]. Cross-cutting relationships with the thrust faults and folds and apparent normal offset imply that the high angle faults record post-Laramide tectonics akin to Basin and Range extension that is well documented in central and northern Mexico and the southwestern U.S. [*Jansma and Lang*, 1997]. Individually, these faults (e.g., the two adjacent to site 6, Figure 1) exhibit dip displacement of as much as 2 km. Although displacements along both thrust and high angle normal faults are substantial, we do not consider them sufficient to call either set of faults accreted terrane boundaries as proposed by some researchers [e.g., *Campa and Coney*, 1983; *Sedlock et al.*, 1993]. In addition, the stratigraphy of rock sequences that are juxtaposed by both types of faults is compatible [*Lang et al.*, 1996], providing further evidence that the structures are not terrane boundaries.

For most of the transect, we adopted the lithostratigraphic nomenclature of *Pantoja-Alor* [1959] and *Fries* [1960] as modified by *Ontiveros-Tarango* [1973], and described in detail in *Johnson et al.* [1991], *Jansma et al.* [1991], *Jansma and Lang* [1997], *Cabral-Cano* [1995], *Cabral-Cano et al.* [1999b], and *Barros* [1995]. In the eastern 40 km, we used the lithostratigraphic nomenclature of *De Cserna et al.* [1980] and *Erben* [1956].

The composite lithostratigraphic column for the transect is over 10 km thick (Figure 2). At the base, in the central map area, is the pre-Jurassic (?) Taxco Schist Formation, exposed in the area northwest of sampling site 10 and at site 8 (Figure 1), its type locality. True schist is rare in the unit. Outcrops are mostly chlorite-grade, light gray sericite-quartz phyllite, whose predominant protolith most likely was rhyolitic ash. The base is not exposed along the transect, but approximately 100 km north at Zacazonapan, the Taxco Schist rests unconformably on granitic basement that is Late Permian-Early Triassic age [*Elias-Herrera and Sanchez-Zavala*, 1990].

East of site 1 (Figure 1) is a region of poorly-exposed chlorite grade metamorphic rock. Metamorphic outcrops are phyllite/schist similar to the Taxco Schist in the vicinity of sample 10; and arkosic metaquartzite and metapelite similar to the Tecomate and upper Cosoltepec formations as described by *Yañez et al.* [1991] and *Weber et al.* [1997] in the Acatlan Complex, 25 km east of Figure 1. We assign these rocks collectively to the Paleozoic(?) Acatlan complex (Figure 2).

Unconformably above the Taxco Schist in the central map area (Figure 1) is the Jurassic-Cretaceous Roca Verde Taxco Viejo Formation (Figure 2). These chlorite and lower grade metamorphic rocks include metasandstone (graywacke) at the top and metaandesite and rare meta-basalt at the base. The color of weathered metaandesite outcrops is a distinct bluish-green, because the rock contains abundant epidote and chlorite. Most metavolcanic outcrops contain agglomerate and/or breccia. Some exhibit pillow structures. Volcanism, therefore, may have been both subareal and subaqueous.

The generally thick bedded Roca Verde grades laterally and may interfinger with greenish gray, thin-bedded, fine-grained siliciclastic and volcanic rock of the Almoloya beds (an informal lithostratigraphic unit of *Cabral-Cano* [1995], and *Cabral-Cano et al.* [1999b]). This unit was only mapped between site 4 and site 6 (Figure 1).

Occupying the same stratigraphic position as Roca Verde-Almoloya strata, but only exposed west of site 9 (Figure 1), is a coarsening-up sequence of predominantly siliciclastic rock that includes the Las Paredes chert (an informal lithostratigraphic unit of *Johnson et al.* [1991]), at the base, and graded sandstone and conglomerate of the San Lucas Formation at the top (Figure 2). The graded sandstone exhibits the same distinctive bluish-green color as weathered metaandesite of the Roca Verde. This suggests that the Roca Verde was a source for San Lucas marine turbidite rocks. The base of these lower Cretaceous-Jurassic(?) strata is not exposed.

Unconformably above the undifferentiated rocks of the Acatlan complex, and only present unconformably below the Morelos Formation in the anticline south of site 17 (Figure 1), is the Middle Jurassic Cualac Formation (Figure 2) [*De Cserna et al.*, 1980; *Erben*, 1956]. This unit is terrestrial conglomerate with granite, quartzite, chert and chlorite-grade phyllite and schist clasts. These exposures are too small to be shown in Figure 1.

Unconformably covering all of these rocks is the mostly Albian Morelos Formation and equivalent strata (Figure 2). These mid-Cretaceous (Late Aptian/ Albian-Turonian), predominantly carbonate strata provide an important lithostratigraphic marker throughout the transect and most of Mexico. Locally, this marker includes the predominantly rudist-facies light gray marine platform limestone and dolostone of the Morelos Formation and the overlying, back reef and bank bioclastic carbonate beds of the Cuautla Formation. Only present on the western end of the transect, where it overlies the Morelos, the Malpaso Formation is a predominantly sandstone, shelf and strandline equivalent of the upper Morelos, the Cuautla, and the Mexcala formations (see below) exposed to the east (Figure 2).

The Morelos grades laterally and/or interfingers with thin bedded, dark-gray to black marl and phyllitic, slatey shale of the basinal facies Pochote beds (Figure 2) (an informal lithostratigraphic unit of *Cabral-Cano* [1995] and *Cabral-Cano et al.* [1999b]).

The Pochote is only exposed between site 6 and site 3 (Figure 1). North of site 6, Pochote beds commonly contain meter-size and larger, mud matrix-supported, angular clasts of massive Morelos limestone. These beds may be debris aprons along the margin of a Morelos platform. The base of the Morelos is an unconformity as evidenced by cobble-size metaandesite clasts of the underlying Roca Verde in a basal conglomerate exposed between site 5 and site 15 (Figure 1).

Late Cretaceous marine shale and sandstone of the Mexcala Formation constitute a flysch sequence in conformable, but sharp, contact with Morelos strata. Influx of these predominantly marine basinal clastics apparently contributed to the demise of Morelos rudist platform environments. East of Iguala (Figure 1), Coniacian sandstone and conglomerate of deltaic origin exists within the Mexcala [*Lang and Frerichs*, 1998]. West of Iguala, Mexcala shale exhibits incipient low grade metamorphism evidenced by dissolution of microfossils and sericite/chlorite mineralization that creates a phyllitic foliation.

Two important mapping errors involving rocks that we assign to the Mexcala Formation appear in the literature. Mexcala strata exposed in footwalls below thrust faults between sampling site 3 and Iguala (Figure 1) appear on some maps as pre-Morelos strata [e.g., *De Cserna*, 1981, 1982, 1983; *INEGI*, 1985a and 1985b]. Apparently, this error was the result of failure to recognize thrust faults at the base of some Morelos exposures, where older Morelos beds rest, in thrust fault contact, on younger Mexcala beds. Also, the west dipping normal Mexcala/Morelos contact that we map from 5 km to 25 km NNE of site 12 (Figure 1) was erroneously mapped as a west-dipping thrust fault, and considered a major terrane boundary by *Centeno-Garcia et al.* [1993a and 1993b] and *Talvera-Mendoza et al.* [1995].

The Mexcala and older units are covered by younger terrestrial rocks (Figure 2). At the base of this cover is well indurated, red pebble-boulder conglomerate, sandstone, and volcaniclastic sandstone/siltstone of the Balsas Formation. Lower Balsas redbeds are folded with the underlying Malpaso, Mexcala and Morelos strata. Upper Balsas beds are not; suggesting an angular unconformity within the Balsas Formation that is exposed at some localities.

These rocks are overlain unconformably by Tertiary lava flows and tuffs, intruded by associated dikes, plugs and larger hypabyssal bodies, and locally hydrothermally metamorphosed. Tertiary volcanic rocks are predominantly rhyolite. Except for the Oligocene Tilzapotla Rhyolite Formation, these rocks are usually undifferentiated in available mapping of the transect. Poorly indurated, fluvial volcaniclastic sandstone and conglomerate are interbedded with the volcanics locally, as are claystone, siltstone and gypsum beds of presumably lacustrine origin.

3. Methods

Between 1990 and 1997 we collected 19 rock samples from the transect for isotopic age determination. Samples were analyzed between 1993 and 1997 by the whole rock K/Ar method at Geochron Laboratories, using their standard procedures.

Samples were collected at the least weathered outcrops that we could access. Material from dozens of potentially useful sampling sites was not analyzed because field and/or laboratory evidence revealed weathering. All sample locations were plotted in the field on 1:50,000 scale Instituto Nacional de Estadística, Geografía e Informática [INEGI] topographic maps, usually with the aid of readings from a hand-held Global Positioning System (GPS) receiver. Each sample consisted of a minimum of 1200 cm^3 of fresh rock, broken off the outcrop using a rock hammer, sledge hammer and/or chisel. The lithology of samples and the absence of evidence of weathering were determined preliminarily in the field using a hand lens. Each sample was assigned to a lithostratigraphic unit and the structural context of each sampling site was determined based on our 1:50,000 scale field mapping.

In the laboratory, each sample was trimmed using a rock saw and a thin section was prepared. Thin sections were examined under a petrographic microscope to confirm that no evidence for weathering could be detected and to refine the field lithologic determinations. A 1 cm^3 specimen was then cut from each trimmed sample and sent to Geochron Laboratories for whole rock K/Ar isotope analysis.

Thin sections and unused sample material are stored at the Jet Propulsion Laboratory's Geology Laboratory. Copies of 1:50,000 scale maps showing sample locations and the analytical reports from Geochron Laboratories are available from the senior author.

4. Results and Discussion

Whole rock K/Ar isotope ages for the 19 rock samples are listed in Table 1. These thermotectonic ages record when the rock samples last cooled through the effective closure temperature of the K/Ar isotope system (~300-350°). Sampling localities are shown on Figure 1. To facilitate discussion, we numbered the samples and assigned them to four age groups in order of decreasing K/Ar isotopic age (Table 1).

Twelve samples were chlorite grade metamorphic rocks, whose stratigraphic position below the mid-Cretaceous Morelos Formation and equivalents requires that their protolith ages must be greater than ~100 Ma. (Note: we consistently use *Harland et al.*'s [1982] geologic time scale.) Because the K/Ar ages for 10 of these metamorphic rocks (samples 3-8, 10-11, and 13-14, Table 1) are younger than 100 Ma, these K/Ar thermotectonic ages must be reset ages; reflecting reheating above and cooling below ~300-350°, subsequent to protolith formation, in response to burial and exhumation/uplift, or following intrusive and/or hydrothermal heating and cooling.

With knowledge of the geothermal gradient at the time of exhumation/uplift, the depth at which these 10 rocks passed through the effective closure temperature of the K/Ar isotope system can be calculated. Thermobarometric analyses of equivalent metamorphic rocks from the San Lucas del Maiz and Zacazonapan localities, 100 km due north of Arcelia (Figure 1), show that the local high geothermal gradient was 70°–90°/km when these 10 rocks last passed through the 300°–350° isotherm [*Elias-Herrera*, 1989 and 1993; *Elias-Herrera and Sanchez-Zavala*, 1990]. Thus, the minimum depth at which the K/Ar isotopic clock was reset for these 10 metamorphic rocks was ~300°/(90°/ km) = 3.3 km. Our K/Ar isotopic ages for these metamorphic rocks require at least two thermotectonic events: 1) their burial below, and 2) their subsequent uplift above a depth of at least -3.3 km.

K/Ar thermotectonic ages of metamorphic rock samples 1 and 2 (Table 1) are older than 100 Ma and could correspond to metamorphic protolith ages. Similarly, the K/Ar thermotectonic ages of the seven unmetamorphosed hypabyssal rocks (samples 9, 12, and 15-19), which are all younger than the stratigraphic ages of the rocks that they intrude, could also correspond to their protolith ages; i.e., when their melts cooled below the 300°-350° effective closure temperature.

A database by *Sedlock et al.* [1993, tables 1-17] shows that since isotope ages of rocks from Mexico were first reported in 1962 [*Damon et al.*, 1962; *De Cserna et al.*, 1962; and *Fries et al.*, 1962], isotope ages of approximately 800 rocks from Mexico have been published. *Oldow et al.* [1989] used a similar database of published isotope ages of rocks from the Sierra Nevada, Canada, and SW Alaska to construct frequency plots showing the number of isotope ages versus time. They identified peaks in these frequency plots that record major thermotectonic events affecting the North American Cordillera. Figure 2 includes a similar frequency plot for Mexico, constructed from the *Sedlock et al.* [1993] database which also covers the Chortis block [*Dengo*, 1975] of Nicaragua and Honduras. On the plot, we identify the age intervals for our four sample groups. For comparison, the figure also includes the frequency plot derived from *Oldow et al.* [1989] which covers the period since ~250 Ma.

The four major thermotectonic events that we record on the Guerrero transect are associated with peaks on the curve derived from the *Sedlock et al.* [1993] database; and, furthermore, the frequency pattern from the *Sedlock et al.* [1993] frequency plot bears a remarkable resemblance to that of *Oldow et al.* [1989] (Figure 2). Because the isotope ages in the *Sedlock et al.* [1993] database are grouped by the terrane where the samples were collected, their ages can be used to delineate other areas of Mexico affected by the four major thermotectonic events that we document only on the Guerrero transect (Figure 3).

In the following paragraphs, we describe the lithology and stratigraphic/ structural context of samples in the four thermotectonic age groups, interpret their local tectonostratigraphic meaning, and discuss their relevance to major thermotectonic events that affected Mexico, the North America Cordillera, and the southern margin of the North America plate.

Group I. We assigned one metamorphic rock (sample 1) to this group (Table 1). It yields a middle Pennsylvanian (Moscovian) age of 301 ±8 Ma. Because this thermotectonic age is older than the mid-Cretaceous stratigraphic age of the overlying Morelos marker, it is not necessarily reset.

This weakly foliated metaquartzite came from the hanging wall of the Papalutla thrust fault near the village of Mexquitlan, which is the westernmost outcrop in a large area of undifferentiated, chlorite-grade metamorphic exposures of the Acatlan complex that constitutes most of the eastern end of the transect (Figure 1).

This sample's Pennsylvania K/Ar age coincides with the initial phase of a thermotectonic event that affected Mexico during late Paleozoic to early Mesozoic time (Figure 3). *Ortega-Gutierrez* [1993], *Yañez et al.* [1991], and *Weber et al.* [1997] report an equivalent age of metamorphism for the Toltepec and Experanza grantoids as well as phyllite of the Cosoltepec Formation in the Acatlan complex east of Figure 1. Similar ages are ubiquitous in northern, eastern and southern Mexico and in the Chortis block (Figure 4).

This thermotectonic event coincides with formation of the Ancestral Rockies and Marathon-Ouachita thrust belt in the western U.S. Cordillera [*Conde*, 1989; *E.L. Miller et al.*, 1992], and the Allegehenian Orogeny in the eastern U.S. Appalachia [*Yañez et al.*, 1991]. Orogenesis resulted from the collision of South America and Africa with North America [*Burchfiel et al.*, 1992; *E.L. Miller et al.*, 1992; *Weber et al.*, 1997; *Yañez et al.*, 1991].

Group II. We assigned one metamorphic rock (sample 2) to this group (Table 1). It yields a Late Triassic (Carnian) age of 221 ±5 Ma. Because this thermotectonic age is older than the mid-Cretaceous stratigraphic age of the overlying Morelos marker, it is not necessarily reset. This phyllite came from a site SE of the village of Papalutla, in the same area of undifferentiated metamorphic exposures of the Acatlan complex as the Group I sample (Figure 1).

This sample's Late Triassic age coincides with the waning phase of the same late Paleozoic to early Mesozoic thermotectonic event recorded by the Group I sample (Figure 3). According to *Yañez et al.* [1991], many small granitic intrusions of this age occur in the type locality of the Acatlan complex. *Cameron and Jones* [1993] report identical ages for granitic plutons in northernmost Mexico. Rocks of this age are ubiquitous in southern Mexico, the Chortis block, and in two northwest trending belts in northern and central Mexico (Figure 4). The frequency plot for the Cordillera north of Mexico shows that equivalent age rocks record initiation of a magmatic event that peaked in Early Jurassic time in the Sierra Nevada batholith and the Canadian Cordillera (Figure 3) [*Oldow et al.*, 1989].

This thermotectonic event coincides with the Sonoman Orogeny, and formation of a continental volcanic arc in western North America that extended from eastern Oregon through southeastern Arizona and into Mexico [*Conde*, 1989; *E.L. Miller et al.*, 1992; *Saleeby and Busby-Spera*, 1992]. Orogenesis resulted from extension and/or transtension in a continental arc system, east of a convergent ocean-continental margin near the western edge of the North America plate [*Saleeby and Busby-Spera*, 1992].

Group III. We assigned eight metamorphic rocks (samples 3-7 and 10-11) and one unmetamorphosed hypabyssal rock (sample 9) to this group (Table 1). They yield an overlapping series of Late Cretaceous (Cenomanian-Campanian) ages from 94.4 ±2.4 Ma to 82.8 ±2.2 Ma (Table 1).

Because the thermotectonic ages of the eight metamorphic samples are all younger than the mid-Cretaceous stratigraphic age of the overlying Morelos marker, they are reset. Seven of these samples were metaandesite from the Roca Verde Taxco Viejo Formation and one was phyllitic schist from the Taxco Schist Formation. All eight were from localities west of Iguala (Figure 1).

These thermotectonic ages date uplift coincident with initiation of local folding and thrust faulting. This interpretation is consistent with biostratigraphic data from the transect, east of Iguala. Siliciclastic strata of the Mexcala Formation are synorogenic flysch contemporaneous with folding and thrust faulting. Abundant fossil planktic foraminifers show that flysch deposition started in Coniacian time (88 Ma ±0.5 Ma) [*Lang and Frerichs*, 1998]. This biostratigraphic age is identical to the mean

K/Ar age of Group III samples. The Coniacian Age is the same as that reported by *De Cserna* [1989] for onset of deformation in the fold-thrust belt of northern Mexico.

The one unmetamorphosed hypabyssal rock (sample 9) in this group is dacite from a plug that cuts the lower, folded part of the Balsas Formation. Because it intrudes a fold near the western edge of the transect, its Santonian Age (83.5 Ma ±2.2 Ma) provides an upper limiting date for the folding. It also shows that the lower part of the Balsas Formation (usually assumed to be wholly Tertiary) includes Santonian or older Late Cretaceous strata.

Sample 9 is the westernmost and oldest of the seven unmetamorphosed hypabyssal rocks that we analyzed (Table 1 and Figure 1). The other six yield ages at least ~33 Ma younger. This age difference suggests that folding and thrust faulting ceased earlier (before ~84 Ma) in the western part of the transect than in the eastern part (before ~51 Ma).

Group III ages coincide with a thermotectonic event that peaked in Mexico during Coniacian to Campanian time (Figure 3). *Grajales-Nishimura et al.* [1993] and *Schaaf et al.* [1993] report identical cooling ages for granitic batholiths along the southern, Pacific margin of Mexico. Likewise, *Elias-Herrera* [1993] reports a coincident uplift age for metaandesite from Zacazonapan. We correlate the Zacazonapan metaandesite with lithologically identical rocks of the Roca Verde Taxco Viejo Formation.

Rocks that are the same ages as Group III samples are ubiquitous throughout Mexico and in the Chortis block (Figure 4). The frequency plot for the Cordillera north of Mexico records similar ages during the waning phase of a magmatic epoch that peaked in Albian time (~100 Ma) in the Sierra Nevada and Canadian Cordillera (Figure 3) [*Oldow et al.*, 1989].

The thermotectonic event recorded by Group III sample ages coincides with the Sevier Orogeny. An east to northeast vergent fold-thrust belt, characterized by thin-skinned tectonics, developed along a wide belt from Alaska to the southern Mexico study area [*Conde*, 1989; *Burchfiel et al.*, 1992; *McGookey et al.*, 1972; *Allmendinger*, 1992; *D.M. Miller et al.*, 1992; *Weber et al.*, 1997]. A retroarc foreland basin formed east of the fold-thrust belt. Orogenesis resulted from contractional deformation east of a relatively steeply-dipping Farallon oceanic plate which was being subducted eastward along the western North America continental margin [*Engebretson et al.*, 1985].

Group IV. We assigned six igneous rocks (samples 12 and 15-19) and two metamorphic rocks (samples 13-14) to this group (Table 1). They yield a series of Early Eocene through Late Oligocene ages from 50.9 ±1.3 Ma to 28.8 ±0.9 Ma (Table 1).

The six unmetamorphosed hypabyssal rocks are andesite (samples 12 and 19), rhyolite (15), and latite (16 and 18) (Table 1), collected from plugs and dikes that cut folds and thrust faults or intrude normal fault planes (Figure 1). Thus, their Early Eocene (50.9 Ma ±1.3 Ma) to Late Oligocene (28.8 Ma ±0.9 Ma) ages which date cooling of the shallow intrusions, flows and pyroclastic deposits provide upper limiting dates for 1) contraction, folding and thrust faulting, and/or 2) subsequent extension, high angle faulting and volcanism.

Both of the metamorphic samples (13 and 14, Table 1) show signs of hydrothermal alteration. Their ages date the same intrusive-extrusive event recorded by the ages of the six unmetamorphosed hypabyssal rocks in this group.

Group IV ages span two thermotectonic events that peaked in Mexico during 1) Middle Eocene and 2) Late Oligocene times (Figure 3). The Eocene event corresponds to the "Balsas Magmatic Event" described by *Pantoja-Alor* [1983] in the Sierra Madre del Sur which includes the study area. *Elias-Herrera* [1993] reports an identical range in ages for samples from granite and diorite stocks and silicic ignimbrites from the Zacazonapan locality, as did *Moran-Zenteno* [1993], *Grajales-Nishimura et al.* [1993] and *Guerrero-Garcia and Herrero-Bervera* [1993] for samples collected south and west of the Guerrero transect.

Rocks that are the same age as Group IV samples are characteristic of the Sierra Madre Occidental and are ubiquitous in Mexico and the Chortis block (Figure 4). The frequency plot for the Cordillera north of Mexico records similar ages during the waning phases of two magmatic epochs that peaked in 1) Early Eocene time (~51 Ma), and 2) Early Oligocene time (~35 Ma) in the Canadian Cordillera and SW Alaska, respectively (Figure 3) [*Oldow et al.*, 1989].

The two thermotectonic events recorded by Group IV sample ages coincide with 1) the late magmatic phase of the Laramide orogeny and 2) an early magmatic phase of Basin and Range extension [*Conde*, 1989; *McGookey et al.*, 1972; *Burchfiel et al.*, 1992]. Orogenesis resulted from contractional and subsequent extensional deformation above a relatively shallow-dipping Farallon oceanic plate which was being subducted eastward along the western North America continental margin.

5. Summary and Conclusions

We report whole rock K/Ar isotope ages for seven unmetamorphosed hypabyssal and 12 chlorite grade metamorphic rocks collected along a 300 km long, W-E geological transect centered in northern Guerrero State, southern Mexico. Based on the reported 70°-90°/km high geothermal gradient at the time their K/Ar clock was reset [*Elias-Herrera*, 1989 and 1993; *Elias-Herrera and Sanchez-Zavala*, 1990], the metamorphic rock ages date thermotectonic events associated with uplift/exhumation above at least -3.3 km. Based on their cross-cutting relationships with folds, thrust faults and extensional faults, the unmetamorphosed hypabyssal rock ages provide upper dates for these structures and magmatic events.

These ages date at least four thermotectonic events that affected the transect, and coincide with major thermal and/or deformational episodes in Mexico and the North American Cordillera from middle Pennsylvanian to Late Oligocene time. These events are:

I. Middle Pennsylvanian (301 Ma ±8 Ma) chlorite-grade metamorphism/ uplift of undifferentiated rocks of the Acatlan complex associated with the Alleghenian Orogeny and formation of the Ancestral Rockies and Marathon-Ouachita thrust belt; due to collision of South America and Africa with eastern North America.

II. Late Triassic (221 Ma ±5 Ma) chlorite-grade metamorphism/uplift of rocks of the Acatlan complex associated with the Sonoman Orogeny and development of a continental volcanic arc in western North America; due to extension/transtension east of a convergent ocean-continental margin along western North America.

III. Late Cretaceous (Cenomanian-Campanian) (94.4 ±2.4 Ma — 82.8 ±2.2 Ma) chlorite-grade metamorphism/uplift of the Roca Verde and Taxco Schist formations and magmatism affecting the lower Balsas Formation associated with the Sevier Orogeny and formation of an east-vergent, thin-skinned, fold-thrust belt from Alaska to southern Mexico; due to contraction east of a steeply dipping Farallon oceanic plate being subducted eastward along the western margin of North America.

IV. Early Eocene-Late Oligocene (50.9 ±1.3 Ma — 28.8 ±0.9 Ma) magmatism, hydrothermal alteration and normal faulting affecting the Roca Verde, San Lucas, Balsas and Tilzapotla formations associated with the late phase of the Laramide Orogeny and early phase of Basin and Range uplift and extension; due to termination of contraction and onset of extension above a shallow dipping Farallon oceanic plate being subducted eastward along the western margin of North America.

If the proposed accretionary terranes of Mexico are indeed "characterized by a geological history which differs from that of neighboring terranes" [*Sedlock et al.*, 1993, p. 10], then one would expect that thermotectonic events affecting each terrane should differ from those affecting its neighbors. Based on our isotopic ages and analysis of ages reported by *Sedlock et al.* [1993, tables 1-17], this is not the case. The coherent map pattern (Figure 4) and age frequency plots (Figure 3) show that most of the present real estate of Mexico was affected by the same four, middle Pennsylvanian (301 Ma) through Late Oligocene (28.8 Ma) thermotectonic events that affected the Guerrero transect and the Mexico and U.S. Cordillera to the north. This conclusion of geographic coherence is further supported by the existence of Oaxaquia [*Ortega-Gutierrez et al.*, 1995; see also *Kesler and Heath*, 1970], which includes crystalline continental basement that links most of the proposed Mexican terranes since Grenvillian (1.0 Ga) and during Paleozoic time (Figure 4).

Our discovery that the K/Ar isotope ages of chlorite-grade metamorphic rocks from the hanging wall of the Papalutla thrust fault are 301 Ma-221 Ma requires revision of one of the stratigraphic correlations in *Lang et al.* [1996, figure 4]. They assign these rocks to the Roca Verde Taxco Viejo Formation [*Fries*, 1960] which has a Jurassic(?)-Cretaceous stratigraphic age. Based on their late Paleozoic-early Mesozoic K/Ar isotope age, these rocks are much older than the Roca Verde ànd probably correlate with undifferentiated chlorite-grade metamorphic rocks at Zacazonapan [*Elias-Herrera and Sanchez-Zavala*, 1990], and/or undifferentiated chlorite grade metamorphic rocks in the Acatlan complex [*Ortega-Gutierrez*, 1981; *Yañez et al.*, 1991].

Our results also require revision of the often assumed, wholly-Tertiary age of the Balsas Formation [e.g., *Fries*, 1960; *Lang et al.*, 1996; *Pantoja-Alor*, 1959]. Because of the 83.5 Ma ±2.2 Ma, Santonian Age of sample 9 (Table 1 and Figure 1), the lower Balsas must include Late Cretaceous strata, at least near the western end of the transect. This age provides new paleoenvironmental information. Biostratigraphic data show that the Mexcalà Formation east of Iguala (Figure 1) contains Santonian marine strata [*Lang and Frerichs*, 1998]. Therefore, deposition of the red, fluvial conglomerate of the lower Balsas Formation on the western end of the transect was contemporaneous with deposition of basinal marine shale and/or deltaic sandstone and conglomerate of the Mexcala Formation, east of Iguala. During Santonian Time, an unmapped terrestrial-marine interface (shoreline) must have existed between these two regions on the Guerrero transect.

Our results provide a basis for recommending future work on the Guerrero transect that was beyond the scope of this study. The easternmost 40 km of the transect (Figure 1), where we assigned diverse chlorite grade metamorphic rocks collectively to the Acatlan complex, is inadequately mapped [*Ortega-Gutierrez*, 1981]. Small scale lithostratigraphic assessment and mapping of this area is essential to provide the stratigraphic and structural data that would reveal the relationships of these low-grade metamorphic rocks with well-mapped, low- and high-grade rocks in the type locality of the Acatlan complex exposed 25 km east of the Guerrero transect [*Yañez et al.*, 1991].

From the standpoint of using isotopic ages to unravel the nature and timing of thermotectonic events affecting the Guerrero transect, our whole rock K/Ar isotopic age results should be considered an initial contribution. Subsequent studies should apply K/Ar, Ar/Ar, Rb/Sr and U/Pb isotopic methods using mineral separates and also fission track dating of zircons to assess further the timing and nature of thermotectonic events that affected the Guerrero transect. In addition to the pre-Morelos metamorphic and igneous rocks, future sampling should include the low grade metamorphic rocks of the Mexcala Formation from west of Iguala, which were not sampled in this study. Important objectives for such work would include 1) determining protolith ages for the metamorphic rocks, 2) refining/testing the significance of our Group I and Group II sample results which are each based on only one sample age, and 3) refining values for the local geothermal gradient from 301 Ma to 28.8 Ma.

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Figure captions

FIGURE 1. Simplified geological map of the Guerrero transect showing locations of sample sites (after *Lang et al.* [1996], and this study). Not shown are Quaternary-Holocene alluvium/colluvium (mostly within areas mapped with dot pattern) and small exposure of Jurassic Cualac Formation (below the Morelos Formation in anticline south of sample site 17). C is the town of Ciudad Altamirano; A, Arcelia; I, Iguala; and T, Tulcingo del Valle.

FIGURE 2. West-East stratigraphic panel diagram for the Guerrero transect (Figure 1), showing stratigraphic relations of lithostratigraphic units (with maximum thickness in m) and their stratigraphic ages. Thicknesses for the Cuautla and Cualac formations (not shown) are 500 m and 800 m, respectively. Letters (cities/towns) and numbers (sample sites) locate sites on Figure 1. See text discussion. (After *Lang et al.* [1996], and this study.)

FIGURE 3. Frequency plot of Devonian and younger isotopic ages in Mexico and composite frequency plot for Sierra Nevada, Canadian Cordillera and SW Alaska, from data in *Sedlock et al.* [1993, tables 1-17] and plotted in *Oldow et al.* [1989, figure 33], respectively. The four age groups recognized in K/Ar isotope ages of 19 rocks from the Guerrero transect are highlighted in gray. Ages in Ma for boundaries of geochronological units are from *Harland et al.* [1982]. Abbreviations for geochronological units are: L, Late; M, Mid; E, Early; MA, Maastrchtian; CA, Campanian;

SCT, Santonian, Coniacian and Turonian; CE, Cenomanian; AL, Albian; AP, Aptian; BA, Barriasian; HA, Hauterivian; VA, Valanginian; BE, Berriasian.

FIGURE 4. Map of Mexico showing Baja California (BC) and the Chortis Block (CB) restored to their pre-Neogene locations according to *Ross and Scotese* [1988]. SMO is the Sierra Madre Occidental, and TMVB, the Trans-Mexican Volcanic Belt. The location of the Guerrero transect is identified by the white rectangle. Map patterns classify purported tectonostratigraphic terranes (delineated in inset map) according to occurrence of isotopic ages corresponding to the four age groups identified in this study (terranes and age data from *Sedlock et al.* [1993]). Oaxaquia is the Grenville age (1.0 Ga) continental craton of Mexico as inferred by *Kesler and Heath* [1970] and mapped by *Ortega-Gutierrez et al.* [1995] using outcrop, borehole and xenolith data. Longitudes/latitudes are present coordinates for North America.

TABLE 1. SAMPLE SUMMARY

SAMPLE NUMBER	LITHOLOGY	FORMATION	K/Ar AGE (Ma)	EPOCH/AGE	AGE GROUP	COMMENTS
1	METAQUARTZITE	ACATLAN COMPLEX	301 ±8	M. PENN	I	UPLIFT
2	PHYLLITE	ACATLAN COMPLEX	221 ±5	L. TRIASSIC	II	UPLIFT
3	METAANDESITE	ROCA VERDE	94.4 ±2.4	CENOMANIAN	III	UPLIFT
4	METAANDESITE	ROCA VERDE	91.9 ±2.4	CENOMANIAN	III	UPLIFT
5	METAANDESITE	ROCA VERDE	91.5 ±2.4	CENOMANIAN	III	UPLIFT
6	METAANDESITE	ROCA VERDE	90.5 ±2.4	TURONIAN	III	UPLIFT
7	METAANDESITE	ROCA VERDE	89.6 ±3.7	TURONIAN	III	UPLIFT
8	PHYLLITIC SCHIST	TAXCO SCHIST	85.0 ±2.2	SANTONIAN	III	UPLIFT
9	DACITE	LOWER BALSAS	83.5 ±2.2	SANTONIAN	III	CUTS FOLD
10	METAANDESITE	ROCA VERDE	83.2 ±2.2	SANTONIAN	III	UPLIFT
11	METAANDESITE	ROCA VERDE	82.8 ±2.2	CAMPANIAN	III	UPLIFT
12	ANDESITE	UPPER BALSAS	50.9 ±1.3	E. EOCENE	IV	CUTS FOLD
13	METAANDESITE	ROCA VERDE	44.1 ±1.1	M. EOCENE	IV	HYDROTHERMAL ALTERATION
14	SANDSTONE	SAN LUCAS	40.6 ±1.3	L. EOCENE	IV	HYDROTHERMAL ALTERATION
15	RHYOLITE	UPPER BALSAS	36.1 ±0.9	E. OLIGOCENE	IV	CUTS THRUST
16	LATITE	UPPER BALSAS	34.0 ±1.1	E. OLIGOCENE	IV	CUTS FOLD AND THRUST
17	ANDESITE	TILZAPOTLA	31.6 ±1.0	L. OLIGOCENE	IV	IN NORMAL FAULT PLANE
18	LATITE	TILZAPOTLA	30.7 ±1.0	L. OLIGOCENE	IV	IN NORMAL FAULT PLANE
19	ANDESITE	TILZAPOTLA	28.8 ±0.9	L. OLIGOCENE	IV	IN NORMAL FAULT PLANE

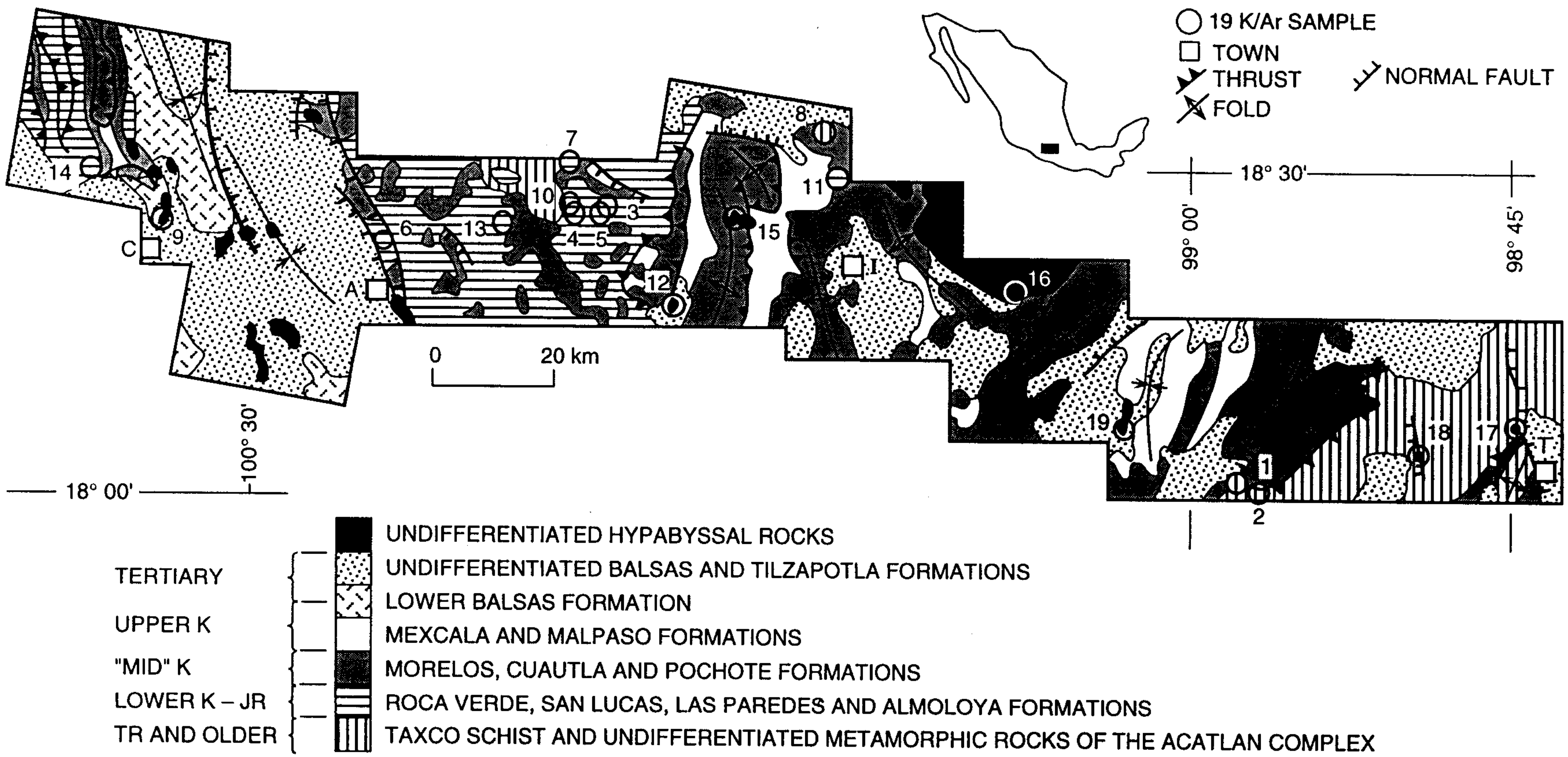


FIG 1 Lang et al.

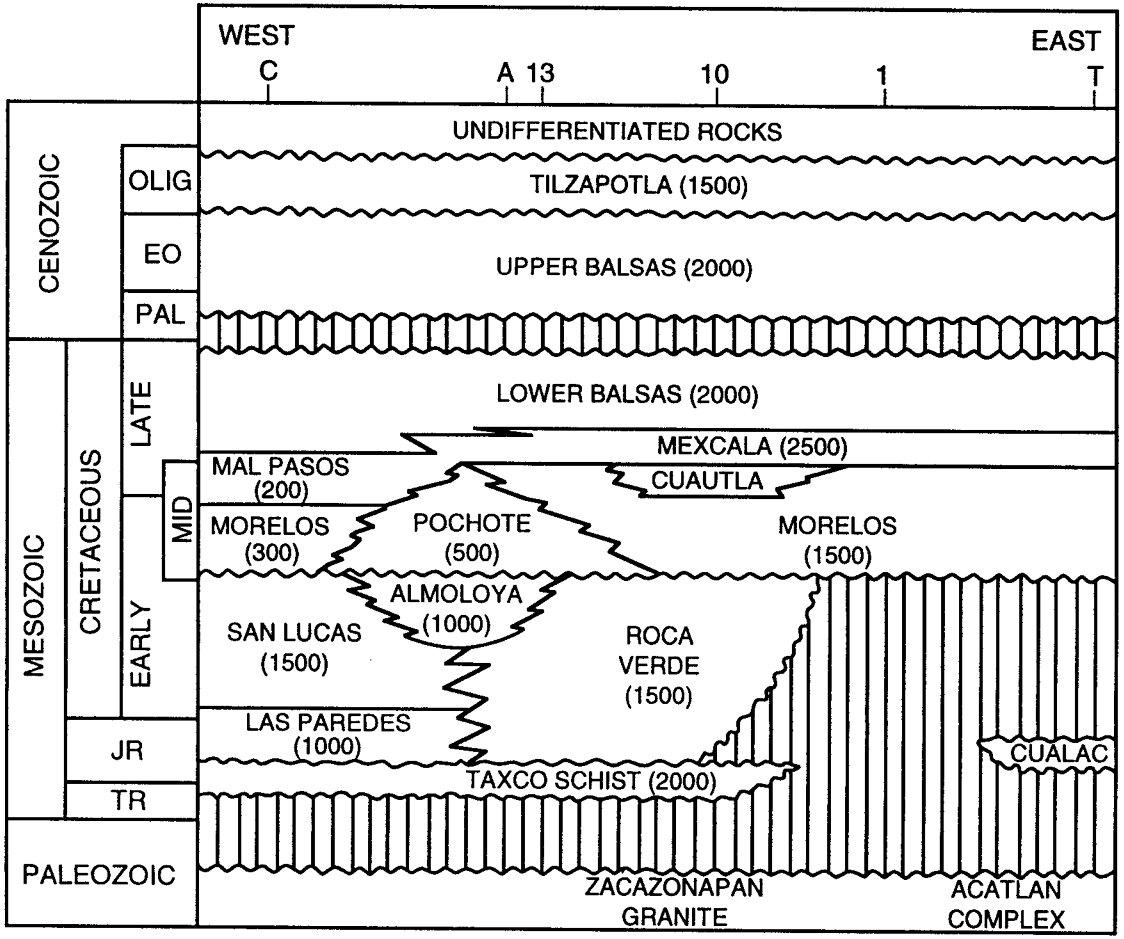
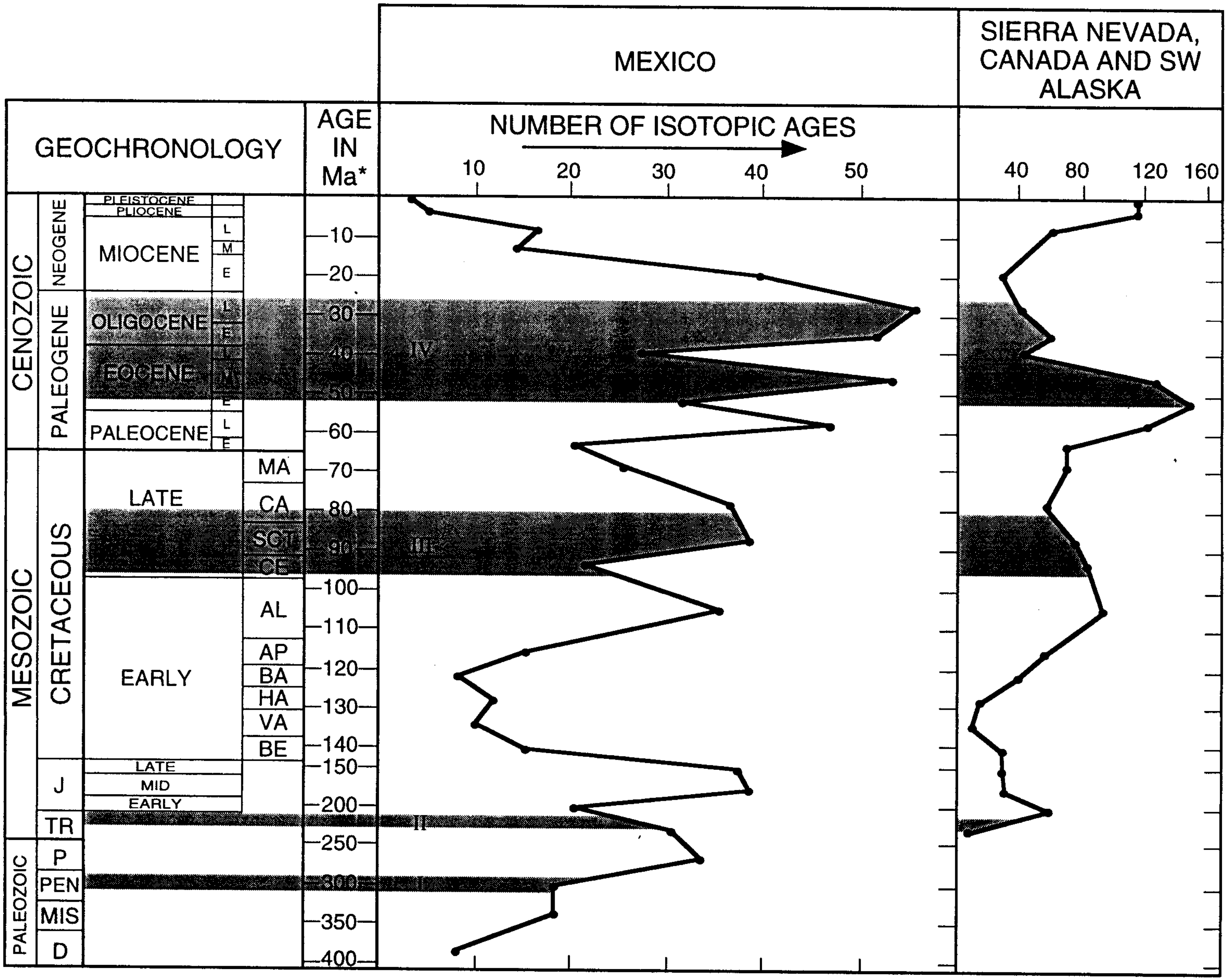


FiG 2 Lang et al.



*SCALE CHANGE AT 150 Ma

FIG 3 Lang et al.

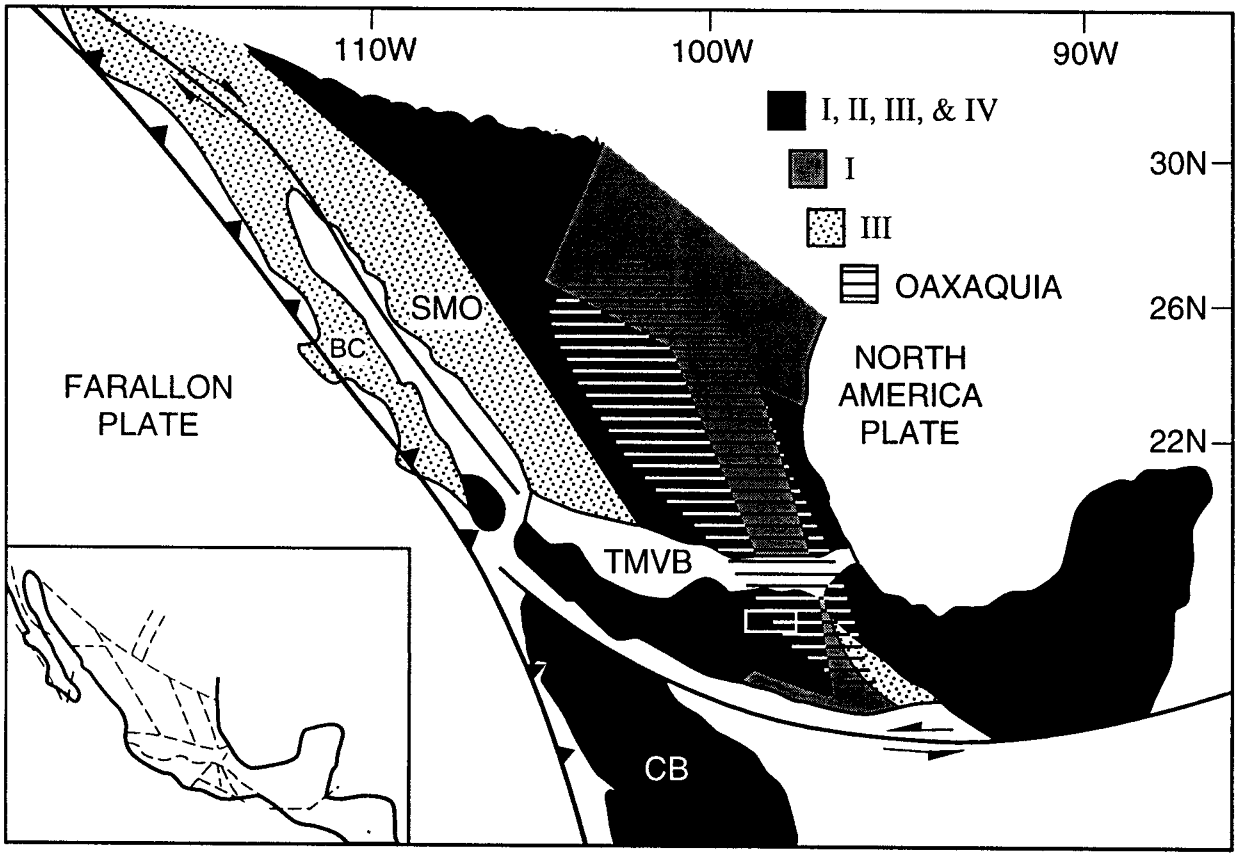


FIG 4 Lang et al.